On the Optimization of the Daily Operation of a Wind-Hydro Power Plant

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Abstract-- **The present paper proposes the utilization of water storage ability to improve wind park operational economic gains and to attenuate the active power output variations due to the intermittence of the wind energy resource. An hourly-discretized optimization algorithm is proposed to identify the optimum daily operational strategy to be followed by the wind turbines and the hydro generation pumping equipments, provided that a wind power forecasting is available. The stochastic characteristics of the wind power are exploited in the approach developed in order to identify an envelope of recommended operational conditions. Three operational conditions were analyzed and the obtained results are presented and discussed.**

Index terms—Wind Energy, Power Systems Economics, Energy Storage, Optimization, Stochastic Processes.

I. INTRODUCTION

THE increasing pressure on the need to intensify the participation of cleaner forms of energy production in the mix of electricity generation fostered the development and growth of wind power energy conversion systems, particularly in the USA and European countries. Although wind energy conversion systems have attained a considerable technological maturity, the power output of these generators is however strongly conditioned by the variable characteristics of the wind resource. This means that dispatchability is rather difficult, namely when the control of the active power generation output is required.

Over the last few years, researches have developed new techniques to improve the output controllability of wind parks and to facilitate its interaction with the energy power market. Kaldellis *et al.* [1, 2] investigated the long-term economic viability of the operation of a wind park cooperating with two water reservoirs, involving a micro hydroelectric power plant and a water pump station. The objective was to store the energy generated by the wind park in low demand periods. Following a market perspective, Halldórsson and Stenzel [3] developed a methodology for the compensation of the wind power output variation exploiting trading contracts. Korpas *et al.* [4] presented a dynamic programming algorithm for scheduling and operation of wind parks, through the management of generic energy storage ability. Billinton and Karki [5] perform an optimal generation analysis of small isolated systems using photovoltaic and wind energy sources, with considerations about the system reliability.

In a previous publication by the authors of this paper [6], the operation strategy of a combined wind-hydro facility (with generation/pumping capabilities) was defined, assuming a deterministic full reliable forecasting for wind power. The implementation of wind-hydro optimization strategies requires the availability of a wind power forecast, which is nowadays possible in time horizons up to 48 hours ahead [7]. In the present paper, wind power forecasting is assumed to be characterized by some uncertainty, as mentioned in [7].

The present paper describes an hourly-discretized optimization algorithm, aiming to identify the optimum daily operational strategy to be followed by both wind turbines and hydro generation pumping equipments, provided that a wind power forecasting is available. The developed approach has two main goals: a) to improve the daily wind park economic operational profit; and b) to smooth the operational power production changes that are due to the natural wind power profile fluctuations, and in this way keep the output power production within upper and lower limits.

As described in [1, 2, 6], water pump/generation facilities are added to a wind park. This storage ability enables: a) to store energy produced in low price periods, to be sold when the daily energy price is high; and b) to store energy in the reservoir in high wind speed periods to be used afterwards for filling wind power gaps, as a complement of the wind park production, helping in fulfilling any contractual commitment with the market or the grid.

In the present analysis, the stochastic characteristics of the wind power are considered by using a time series, for a time horizon of 48 hours, of average values and standard deviations representing the wind power forecast. Through Monte Carlo simulations, wind power time series scenarios are determined. For each one of them, an optimized daily operation strategy is determined by solving a linear hourly-discretized optimization problem. In the present study, the objective function was formulated in order to improve the combined wind-hydro operational economic profit. Output

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active power limits of the wind park are explicitly considered in the formulation, dealing in this way with either network operational restrictions or market agreements. Other operational limitations are also taken into account in this formulation. The proposed algorithm accomplishes to identify the best operation strategy of a combined wind-hydro power plant with little water storage ability, determining the amounts of wind and hydropower to be generated for each hourly period. Pumping power consumption and storage level profiles are also calculated for every hour.

The actual Portuguese wind energy remuneration tariffs for wind power generation are used in this work to illustrate the economic gains that can be obtained with the implementation of the operational strategy. However, in the proposed methodology electricity market forecasted prices can also be used to value energy in different daily periods. Although only active power injection is considered in the present formulation, reactive power targets can easily be added to the problem. In this way, also operation profits resulting from a participation in an ancillary services market could be considered.

II. THE OPERATION ALGORITHM

The proposed model was developed exploiting two ideas: a) the capability of controlling a portion of the wind park power production, assuring a minimum power delivery to the grid, no matter the wind speed conditions; and b) the utilization of a stochastic variable to represent the wind speed forecasting.

To increase its competitiveness in the energy market and to increase its operational value, wind parks should be able to guarantee, at the beginning of the day, energy availability for up to 24 hourly periods ahead. Instead of controllable generation plants, electricity production by wind depends of the variations in the primary source of energy. The accuracy of the forecasted wind power and the energy storage ability should enable the determination of the width of an output generation interval for the hours ahead.

To improve the output controllability of the wind generation, an hydro system is added to the wind park, consisting of: a) a water pump station that elevates water from a source (i.e. river, lake, reservoir) to an upper water reservoir, using exclusively the electric power produced by the wind generators; b) a mini hydroelectric power plant (eventually, these latter two equipments can be replaced by a single reversible hydraulic pump/turbine); c) penstock and pumping pipes. Although the hydraulic equipments and the wind park can be located in different places, in the present work an electrical proximity between them is assumed.

A. Input Data

Besides the physical characteristics of the wind-hydro system, the model needs the following input data to calculate the estimated operation in the study horizon: forecasts of wind power or wind speed, active power price estimation and desired output limit curves (eventually to be defined by the system operator according to operational constraints).

As mentioned before, a forecast of wind speed or wind power is needed. The development of prediction methods in this area [7, 8, 9, 12] allows to calculate the wind power for the next 48-hours with reasonable accuracy. As in [7], independently of the prediction method used for wind power forecasting, errors practiced in previous wind power forecasts for different time horizon periods (1-hour ahead, 2-hours ahead, and so on) can be collected. With these values, an error distribution curve for each time horizon period can be obtained. Following a simplified approach based in [7], from the error distribution curve and the predicted wind power, the expected standard deviation of the wind power in each time period can be estimated, assuming a Gaussian distribution. Exploiting this approach, the present formulation assumes that wind power predictions are represented through its average value and deviation values for each time period of the study horizon. A wind speed forecast can also be used in this approach, assuming that the corresponding wind power forecast is obtained afterwards exploiting the wind generators power curve characteristics.

Following the EU directive on renewable energies [13], system operators in Europe are obliged to give priority to all the renewable energy production, independently of the moment of the day. However, such a policy may create several technical problems since a large integration of wind generation is taking place at either distribution or transmission networks. As a result, very strict limits are being imposed to the capacity to be installed in the wind parks in order to avoid stressing the network. However, as this approach is too restrictive, once maximum wind power has a small probability of occurrence, the system operator is allowing, in some cases, that the installed capacity can be larger than what the network would allow, if the wind park owners accept an interruptability generation policy. Such a situation requires the development of new integrated management policies to help managing these kinds of generation facilities. The approach described in this paper is providing an optimization tool for these purposes. In cases where the property of wind parks and large pumping storage units is the same, a global optimization of the generation portfolio of the generating company can be envisaged, extending the approach described here.

In Portugal, wind energy is remunerated according to known tariffs that may include an hourly modulation coefficient, aiming to increase the participation of renewable generation during peak hours. This scheme aims to reduce the needs on conventional thermal production, even if this price is larger than the market price of the thermal production in these peak periods. Therefore, the active energy price curve is considered as known in advance. As the hydro system of the Wind-Hydro (W-H) plant only stores wind energy type, it is assumed that all W-H production is remunerated as wind energy, which, in Portugal, is better remunerated than hydro energy. Other gains for the system that could result from the increase in controllability of the wind parks (namely, contributions for secondary reserves and others) are neither recognized nor remunerated. In other countries, in which the price is not established with anteriority, a curve of estimated market prices [14, 15] could be used in this algorithm.

As referred previously, the increased participation of non-controllable generators in system operation could lead, in some scenarios, to network branch congestion problems that reduce the system ability to accept the full wind parks production. The inclusions of power exchange limits between the wind park and the grid is therefore important when defining the wind park operation strategy. At the same time, in a market environment, the ability of production control of the wind generation facility will improve the possibility of having some kind of market participation in terms of energy amounts. In order to deal with these operational restrictions, the proposed approach uses two vectors that represent the hourly limits to be imposed to the W-H output production, as a result of network restrictions and market requirements.

B. The Optimization Problem

In this work, the maximization of the 24-hours operational profit of the W-H power plant is wanted. For that purpose, an optimization problem was formulated, through the maximization of the economic gain that results from the energy delivered to the grid, considering the main operational restrictions of the W-H system and a discretization in 24 hourly periods. The solution of this problem provides an operational strategy to be followed by the wind, hydro generator / pumping units during the next hours.

In the present work, the available wind power is assumed as a stochastic quantity, represented by two series of hourly values: the wind power average value and its standard deviation magnitude. The algorithm randomly obtains *S* samples of available wind power series, each of them representing a wind power scenario. Sample vectors of the available wind power Pv characterize these scenarios. For each scenario, the following optimization problem is solved:

$$\text{Max. } \sum_{i=1}^{n}\left(c_i\, P_i - cp\, Pp_i\right) + n\, c_\alpha\, \alpha \qquad (1)$$

$$\text{s.t.} \quad P_i = Pw_i + Ph_i \qquad (2)$$

$$Pv_i = Pw_i + Pp_i + P_{DLi} \qquad (3)$$

$$E_{i+1} = E_i + t\, \left(\eta_p\, Pp_i - \frac{Ph_i}{\eta_h}\right) \qquad (4)$$

$$E_1 = E_1^{esp} \qquad (5)$$

$$E_{n+1} = E_{n+1}^{esp} \qquad (6)$$

$$\alpha\, P_i^L \le P_i \le P_i^U \qquad (7)$$

$$Pg^L \le \left(Pw_i + Pp_i\right) \le Pg^U \qquad (8)$$

$$Ph^L \le Ph_i \le \min\left(Ph^U, \eta_h\, \frac{E_i}{t}\right) \qquad (9)$$

$$Pp^L \le Pp_i \le Pp^U \qquad (10)$$

$$0 \le E_i \le E^U \qquad (11)$$

$$0 \le \alpha \le 1.0 \qquad (12)$$

$$P_{DLi} > 0 \qquad (13)$$

$$i = 1, \dots, n$$

Where the variables are vectors describing: P, hourly active powers delivered to the network by the wind-hydro facility; Pw, hourly active powers delivered to the network by the wind generator; Ph, hourly active powers produced by the hydro generator; Pp, hourly average active power consumed by the water pump station; P_{DL}, hourly dumping power loads, i.e.: part of the active energy of the wind power curve not used to generate electricity (equivalent to wind energy to be curtailed or reduced, if technologically possible); E, energy storage levels in the reservoir in each hour. In this formulation, α is a variable that represents a decrease factor in the output lower limit.

The following parameters were also defined: P^L and P^U representing respectively hourly vectors of minimum and maximum power output limits related with market requirements and network restrictions; Pv, hourly vector of available wind power in the considered scenario; c, vector of hourly active power prices; cp, pump operation cost; c_α, penalty for generation below the lower output limit; E^U, reservoir storage capacity; η_p, efficiency of water pump station and water pipes network; η_h, efficiency of the water reservoir and hydro generator; E_1^{esp} and E_{n+1}^{esp}, initial and final levels of the reservoir, respectively; Pg^L and Pg^U, lower and upper power capacity limits of the wind park, respectively; Ph^L and Ph^U, lower and upper production power limits of the hydro generator, respectively; Pp^L and Pp^U, lower and upper physical power limits of the pump station, respectively; t, duration of each interval (1 hour in this case); n, number of discrete intervals.

From the observation of the objective function (1), one can identify two terms:

- the first aims to maximize the profit in the active hourly power (energy) delivered by the W-H plant to the grid, considering the internal pumping cost;
- the second component seeks to perform the requirement of delivering to the network a minimum output power. When there are no possibilities to follow the schedule plan (the available wind power plus the power that can be produced from the stored energy is below the lower output limit), the lower output bound is reduced using a $\alpha < 1.0$. In those cases where the combined W-H operation can compensate an eventual wind power shortage with power from water-stored energy, the variable $\alpha = 1.0$. As the lower limit should be respected in all the *n* intervals, the expression $\left(c_\alpha\ \alpha\right)$ is multiplied by the number of discretization periods.

As shown in (2), both the hydro production and the portion of the available wind power directly delivered to the grid constitute the output hourly active power of the W-H plant.

From (3), a fraction of the hourly available wind power is directly supplied to the grid during the considered interval. Another portion of this can be stored (by using the hydro components) and delivered in subsequent intervals. In some particular cases, it may happen that a part of the available wind energy could not be used.

Equation (4) describes the energy balance in the reservoir. At the beginning of the *(i+1)*-interval, the energy in the reservoir is the initial level in the *i*-interval plus the pumped energy, minus the energy supplied to the grid by the hydro generation during that same interval.

In the proposed formulation, both the initial and final energy levels of the reservoir should be specified, as described by equations (5) and (6). The initial level is known, because it is the final level of the previous day. However, the optimal final level of the current day is unknown and depends on the expected operation strategy to be defined for the next day. In order to obtain an optimal value for the reservoir level, the original study horizon (24 hours) is extended one day ahead, resulting in 48 hourly periods. As the W-H operation is daily performed, only the first 24 periods are used.

It would be desirable that the output power of the generation facility would remain within a given range, as shown in (7). These output limits could represent: a) operational restrictions of the network, usually associated to the thermal limits of the critical branch in the grid or stability constraints, if imposed in certain periods of operation; b) contractual limitations resulting from the participation of the wind park in market negotiation platforms (daily market or bilateral contracts).

Equations (8)-(11) describe the operational restrictions of the wind and hydro generators, pumping units and storage capacity. As shown in (9), the maximum hourly hydro generation level depends on the generation equipment limits and on the available energy in the reservoir for that interval.

In the presented formulation, equations (1)-(13) represent a linear optimization problem with 289 variables, 145 equality constraints and 530 inequalities. This problem is solved using a Predictor-Corrector Primal-Dual Interior Point Method [16]. However, any other linear optimization methods could also be used.

C. Output Data

The solution of the optimisation problem (1)-(13) provides the hourly active power to be generated by the hydro and wind generators during each of the 24 hours. Storage levels and the pump operational strategy in the period are also determined, assuming that wind power is supposed constant during each period. When wind power forecasts are available in reduced time step intervals, an increase in the detail of the solution profile can be obtained.

In real on-line operation, namely during the pumping unit switch-on moment, the W-H global output could be momentarily less than the lower limit defined for the global generation facility. In this case, the simultaneous operation of both pump and hydro-generator units could restore the bounded operation. As in the present paper hourly operation is analysed, the possible costs related with the simultaneous pump/hydro operation are not considered.

After the *S* simulations, average, maximum and minimum values of the relevant variables are obtained. These values are used to represent the proposed operation strategy for the next hours and to evaluate the performance of the solutions.

A minor modification of the proposed algorithm allows the identification of the maximum lower limit of the output generation band of the W-H facility for a pre-specified wind forecast scenario. If in equation (12), α has not a superior bound (a large value can be used), $c_\alpha >> c$ and $c_\alpha >> cp$, the optimization algorithm aims to identify a strategy that will increase the lower output limit of the generation facility. Results of simulations for such a situation are shown in Section III. As the spinning reserve to be hourly settled for the next day by the system operator is related to the lower limit output that the wind parks are able to guaranteed for all the 24 hour period, a W-H operation aiming to increase this lower limit could reduce the reserve needs and the corresponding ancillary services cost of the system.

III. RESULTS

To test the quality of the proposed methodology, the W-H generation facility described in Table 1 is used.

TABLE 1
WIND-HYDRO POWER PLANT CHARACTERISTICS

Pg^U [MW]	Ph^U [MW]	Pp^U [MW]	c_α [€/MWh]	cp [€/MWh]
12	3	3	500	1.5

E^U [MWh]	E_1^{esp} [MWh]	E_{n+1}^{esp} [MWh]	η_L	Turbines
24	0	0	0.75	6x2 [MW]

In Table 1, $\eta_L = \eta_h * \eta_p$ is the global hydraulic circuit efficiency, here assumed to be 75%, a typical value with the nowadays technology. Both maximum hydro generation and pump nominal capacity are considered 25% of the wind park installed capacity. The penalty for generation below the lower output limit (c_α) should be a large value, aiming to verify this restriction. In the present work, a value approximately 5 times the best wind power price is used. The cost of the pumping operation (*cp*) only represents internal operational costs. It must be stressed that both the efficiency and the electrical consumption of the pumping units are explicitly represented in the mathematical problem formulation. The water reservoir is considered to be able to store energy corresponding to 2 hours of full operation at nominal power of the wind generators. It is assumed that this reservoir starts empty and it will not keep energy after the 48-hours of simulation. It must be stressed however that this approach enables the identification of the optimum reservoir level after the first 24 hours of operation, using for that purpose information related with a 48 hours time horizon. Six turbines of 2 MW each are supposed to be installed in the wind park, as mentioned in Table 1.

The stochastic characteristics of the wind power forecast used in this research are shown in Fig. 1.

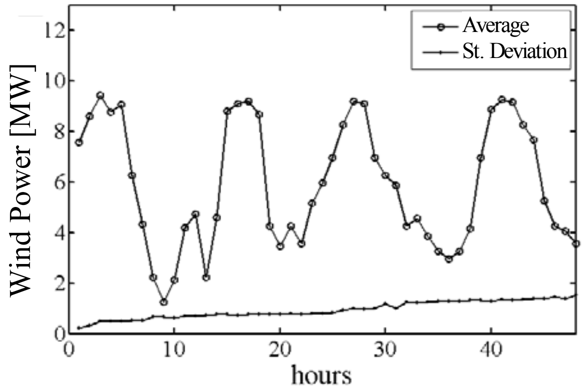


Fig. 1. Available Wind Power– Average and Standard Deviation Values

As in [7], Fig. 1 shows that uncertainties in the available wind power forecasts for different time periods are related with the prediction time horizon. Generally, forecasts for long periods present larger errors, here described by larger standard deviation values. By considering the stochastic characteristics of the available wind power (Fig. 1), $S = 150$ Monte-Carlo simulations were performed. For each of them, the problem (1)-(13) is solved. This enables to get a view of the set of operational solutions considering the wind power stochastic characteristics. In this way, it is possible to identify an envelope for the output power of the W-H facility.

As previously mentioned, the Portuguese wind energy remuneration is defined for specific tariffs [10, 11], independently of the market price. By exploiting the mechanisms defined in these tariffs, the following prices for wind energy were used for the *ith* day hours: c_i=54 €/MWh $0 \le i < 8$ and $22 \le i < 24$; c_i=103.84 €/MWh for $8 \le i < 22$. As shown, the remuneration is larger during the off-valley hours. In the proposed algorithm, an hourly vector contains the energy price for every hour of the following day. Either forecasted spot prices or bilateral contract prices could also be used instead.

Three sets of operational conditions were considered, as described in Table 2, to evaluate the flexibility of the approach and the profit gains that can be obtained when following the operation strategies.

TABLE 2 -TEST CASES

Case (A)	$(\alpha\ 3)$ MW $\le P_i \le$ 8 MW , $\forall i$
Case (B)	$(\alpha\ 3)$ MW $\le P_i \le$ 8 MW $8 \le i < 22$
Case (C)	$\left.\begin{matrix}(\alpha\ 3) \text{ MW} \le P_i \le 8 \text{ MW} \\ 0 \le \alpha \le 999\end{matrix}\right\} \forall i$

In Table 2, Case (A) considers output power operational band restrictions in all periods of the day. Case (B) only represents output hourly power restrictions during the off-valley hours (corresponding to the high price periods of the Portuguese tariffs for wind energy). Generally, the transmission grid is also more stressed in these periods. Case (C) also considers output restrictions in all hourly periods. However, if α is restricted by a large value (instead of Case (A)), the proposed algorithm seeks the maximum lower limit in the output power band. In the three cases, the same restrictions are maintained for the second day of operation.

The W-H identified strategies are compared with the Only Wind (OW) operation strategy. In this OW operation, the upper restrictions on active power generation to be delivered to the grid (8 MW, as defined in Table 2) were solved by a reduction in the amount of turbines in operation. To represent this limitation in OW operation, a simple approach was used: when the forecasted average value for the available wind power was larger than 6.5 MW, two wind turbines were disconnected. This strategy was adopted since when the average wind power value is larger than 6.5 MW the probability of having a wind power generation larger than 8 MW is very large, requiring, under an OW operation, either the adoption of an interruptability procedure or new output power control technologies (not considered in the present case). This means, that when the average wind power is below 6.5 MW, all the 6 turbines are operating, improving the global OW operation strategy. It must be stressed that this OW strategy only considers the upper output limit. In a conventional wind park (without storage ability) there are no possibilities to follow the lower power output limit that should be delivered to the grid, according to possible contractual commitments. In Fig. 2, this OW operation is described.

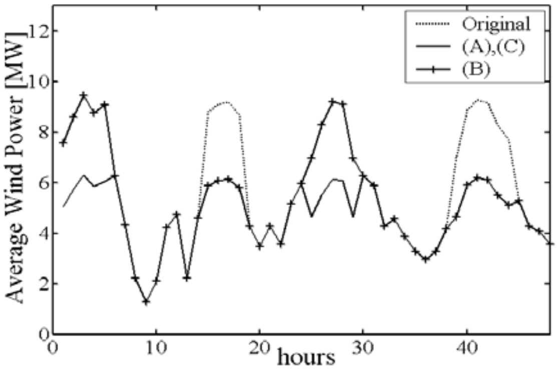


Fig. 2. OW Operation – Wind Average Values for Cases (A), (B) and (C)

As Fig. 2 shows, in both Cases (A) and (C) the average value of the wind power never overpasses 6.5 MW. In Case (B), turbines are only disconnected (when necessary) during off-valley hours. The stochastic standard deviation of the wind is not modified at any case. With the average values of Fig. 2 and the standard deviation of Fig. 1, wind power series are obtained in each Monte-Carlo simulation. In the next section, the operational profit results are presented and discussed.

A. Profits

Table 3 presents the gains obtained when using the W-H operation strategies comparatively to the OW operation, for the first 24 hours of simulation.

TABLE 3
W-H VS. OW

		Case (A)	Case (B)	Case(C)
Profits	OW [€]			
	Average	8881	9692	8837
	W-H [€]			
	Average	10845	10857	10754
W-H vs. OW Gains	Daily [€]			
	Min.	1786	1100	1696
	Average	1964	1165	1917
	Max.	2084	1235	2121
	Percent [%]			
	Min.	19.6	11.1	18.5
	Average	22.2	12.0	21.7
	Max.	25.5	13.4	25.1
	Annual [k€]			
	Min.	651.8	401.1	618.9
	Average	716.9	425.3	700.1
	Max.	760.8	451.1	774.1

As illustrated in Table 3, the elimination of the constraint restrictions in the low price periods (Case (B)) increases the OW strategy profit in 811 € (9.13%) in the first 24-hours of operation. This profit increase is expected when, in low price periods, there is wind power available above the restriction limit (as showed in Fig. 2), which could be sold to the grid if no turbines release is required. However, the profit difference between Cases (A) and (B) in W-H strategy is minor (12 €, 0.11%). As the W-H approach can store the available wind power when upper limits are present, all the turbines are operational in the cases of the present study. Additionally, W-H strategy seeks to supply energy to the grid in upper price periods (when possible), therefore its operation is not beneficed in Case (B). Alternately, the increase in the lower limit (Case (C)) slightly reduces the W-H profit, when compared with Case (A) (91 €, 0.84%). This reduction is probably due to a decrease in the space of solutions of the problem (1)-(13).

The gains between W-H and OW strategies are also showed in Table 3. When there are output restrictions in all periods (Case (A)), the gain between these operations remains in a range between 19.6 and 25.5 %, with an average value of 22.2 %. Expressing this gain in yearly values, if the wind power conditions (as described in Fig. 1) would remain all the year, the expected average gain would be 716.9 k€. When output restrictions are considered only in off-valley hours (Case (B)), the utilization of the storage ability results in average gains of 12%, or in an annual profit increases of 425.3 k€. Case (B) presents yearly gains 41% lower than Case (A). The storage ability allows two types of gains: a) those resulting from the hourly price differences; and b) those obtained from storing energy when upper power output restrictions are reached, and selling this energy in the next periods. Case (B) has the same price profile than Case (A). However, the reduction in the number of periods with output power restrictions results in smaller profit gains.

Case (C) aims to increase the lower output power limit of the combined wind-hydro facility, when output restrictions are considered during all hourly periods. This scenario leads to slightly decreased gains regarding the ones obtained in Case (A) (2% smaller), with an yearly expected gain of 700.1 k€. Table 4 presents the expected lower power output limits that can be obtained when adopting this operational strategy.

TABLE 4
LOWER POWER LIMIT VALUE

	Case(C)	
	α	Lower Power Limit [MW]
Daily values		
Min.	1.0113	3.0339
Average	1.3095	3.9285
Max.	1.6850	5.0550

From the results of the simulations performed for Case (C), described in Table 4, it is possible to identify that an increase in the lower output power limit can be obtained. The higher value that the W-H operation could guarantee in all the hours is increased in a range from 1.13% to 68.50 % of the proposed lower output limit (3 MW), an average supplement of 30.95 %. This effort in trying to increase the lower power output limit of the W-H facility was, however, not subjected to any additional remuneration. It must be stressed that in all simulations of both Cases (A) and (B), it was not required to decrease the specified lower limit (3.0 MW), resulting in $\alpha = 1.0$.

Having in mind that the wind power industry compares the performance of a wind park in terms of equivalent number of hours per year working at nominal power, a comparison among the different operating strategies was performed assuming that the wind power characteristics were the same for all the days of the year. In Table 5, differences in energy production resulting from the adoption of these different operating strategies are described.

TABLE 5
W-H AND OW – ANNUAL NUMBER OF HOURS WORKING AT NOMINAL POWER

	Case (A)	Case (B)	Case(C)
OW [h]			
Min.	2432	2756	2391
Average	2610	2942	2600
Max.	2753	3135	2798
W-H [h]			
Min.	2899	2922	2899
Average	3104	3107	3109
Max.	3260	3308	3316

The objective function of the optimization problem (1)-(13) is to improve the W-H economic profit. However, an increase in the expected number of equivalent annual hours operating at nominal power is obtained. In Case (A), the W-H strategy increases, in average, this value from 2,610 hours (OW operation) to 3,104 hours, a yearly average increase of 18.93%. In Cases (B) and (C), the percentage increases are 5.61 and 19.58%, respectively. As the economical gain is not exclusively related with the number of equivalent hours operating at nominal power (also depending of the price behavior, among other factors), the increments in this parameter are lower than those described in Table 3.

B. W-H Behavior

An example of the W-H operation strategy (in average values of Case (A)) is described in Fig. 3, for the storage levels and pumping consumptions.

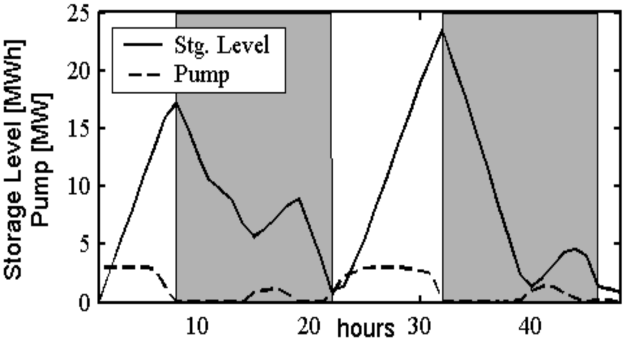


Fig. 3. W-H Operation – Case (A) – Average Storage Levels and Pump Station Consummations

As Fig. 3 shows, the pump station stores water in the upper reservoir in the two first low price periods (white boxes). In high price periods (gray boxes), the pump station only operates when the maximum output restrictions are reached. As depicted, the energy stored in the reservoir is increased in low price periods and during network congestion situations, to be sold with preference in high price periods. Because the reservoir is empty at the first hour and the pump capacity is limited, the maximum storage capacity is only reached at the beginning of the second high price period. It must be stressed that the reservoir level is not empty at hour 24. The utilization of the information of a second day forecast allows obtaining an optimum value of 3.31 MWh (13.8% of the maximum storage ability) at hour 24, aiming to optimise the next day operation.

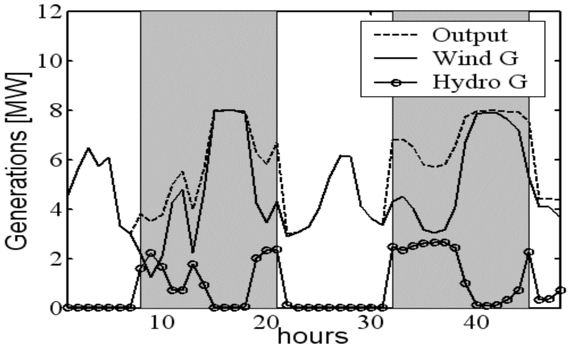


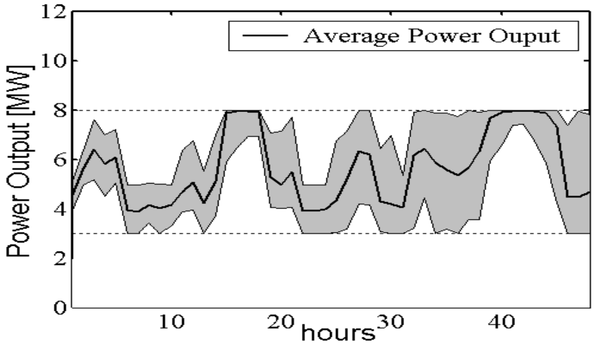
Fig. 4. W-H Operation – Case (A) – Average Output, Wind and Hydro Active Power Generations

In Fig. 4, average values of the W-H facility output, as well as of the wind and hydro generators productions, are described, for the simulations performed for Case (A). As shown in this figure, in low price periods all output generation comes from the wind generators. In these periods, additional wind energy is used to pump water to the upper reservoir (Fig. 3). On the other hand, the power supplied by the W-H plant in high price periods is obtained from both wind and hydro generators. In these hours, the hydro generation is added to the available wind power production to increase the total active power supplied to the network, as far as possible. When the upper output generation limit is reached, the hydro generation is not used, the maximum of the wind generation accepted by the network is delivered to the grid, and the remaining wind production is stored in the reservoir through the pumping station (as showed in Fig. 3).

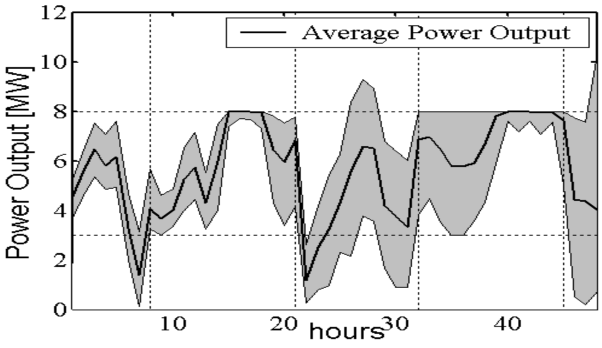
The optimization approach used to deal with the W-H operation can also allow controlling ramp up and down output generation variations of the W-H plant, improving the dynamical behavior of the global system operation. This can be done by specifying additional restrictions related with limits in the maximum active output power variation between consecutive periods. These additional restrictions generally result in lowering the W-H vs. OW operational gains. These restrictions have not been included in the present formulation, since generally system operators are not requiring such behavior in wind power generation.

C. Output Limits

Fig. 5.a shows the results of the optimisation algorithm, identifying the operation strategy that can be followed for Case (A). Due the stochastic behaviour of the wind power, these results include average, maximum and minimum values for the W-H hourly active power generation of the combined facility, providing an envelope of operational conditions (the shaded area). As it can be seen from this figure the specified output power restrictions have been always respected.



(a) – Case (A)



(b) – Case (B)

Fig. 5. W-H Operation – Output Hourly Active Power

Fig. 5.b shows the W-H power output limits and the variation in the average hourly active power supplied to the grid for the simulations performed for Case (B). By comparing Fig. 5.a and 5.b, the effectiveness and quality of the proposed methodology can be observed. When output limits are not included during valley hours, the operation strategy identified (Fig. 5.b) often reaches values out of the range defined for Case (A). As shown, at hours 8, 23 and 24 the average power output value of the obtained from the simulations is below the lower output limit. However, when generation output limits are required to be followed in all periods (Fig. 5.a), the proposed strategy restricts the W-H production between limits in all simulations.

The output power trajectory of Cases (A) and (C) (this latter, not presented in the paper) are similar.

IV. CONCLUSIONS

In this paper, an optimization approach was developed to identify the best-combined daily operation strategy to be adopted in a wind and small hydro generation / pumping facility. The utilization of the water storage ability allows an increase in the wind park economic profit, since wind energy is preferentially delivered to the network during the off-valley hours (higher price intervals). In these periods, the available wind generation is complemented with hydro generation, when possible. When in low price periods or network congestion situations, the pump station is used to enlarge the water reservoir levels. Three test conditions were analyzed, considering Portuguese wind energy remuneration conditions. When compared with the only wind operation (i.e. without hydro components), the predicted yearly average economic gain of the wind-hydro strategy is between 425.3 and 716.9 k€, for the analyzed test case.

By using the water storage ability, it is possible to deal with any network operational restrictions that usually limit the capacity to be installed in a wind park. This approach also increases the controllability of the generation output of the wind park, aiming to improve the participation of wind generation in electricity markets. A decrease in the needs on conventional capacity reserves, to be managed by the system operator, can be also obtained, since there will be a reduction on intermittence of the energy injected into grid.

The increase of wind energy penetration in power systems attained a stage that recommends the use of storage capabilities in order to avoid system operational problems. The identification of combined operation strategies for very large wind parks and large water storage hydro facilities will be the next step to be developed.

V. REFERENCES

[1] J.K. Kaldellis, K.A. Kavadias and D.S. Vlachou, "Electricity load management of APS using wind-hydro solution," in *Proc. Wind Power 2002*. Athens, Greece.

[2] J.K. Kaldellis and K.A. Kavadias, "Optimal wind-hydro solution for Aegean Sea Islands' electricity demand fulfilment," *Journal of Applied Energy*, vol. 70, pp. 333-354. 2001

[3] K. Halldórsson and J. Stenzel, "A scheduling strategy for a renewable power marketer," in *Proc. of 2001 IEEE Porto Power Tech Conf.* Sept. 2001, Porto, Portugal.

[4] M. Korpas, R. Hildrum and A.T. Holen, "Operation and sizing of energy storage for wind power plants in a market system," in *Proc. 14th PSCC*. June 2002, Sevilla, Spain.

[5] R. Billinton and R. Karki, "Capacity expansion of small isolated power systems using PV and wind energy", *IEEE Trans. On Power Systems,* vol. 16, nº 4, Nov. 2001.

[6] E.D. Castronuovo and J.A. Peças Lopes, "Wind and small-hydro generation. An optimisation approach for daily integrated operation," in *Proc. 2003 EWEA*. Madrid, Spain, June 2003.

[7] P. Pinson and G.N. Kariniotakis, "Wind power forecasting using fuzzy neural networks enhanced with on-line prediction risk assessment," in *Proc. 2003 IEEE Bologna Power Tech Conf.*, June 23th-26th, Bologna, Italy.

[8] Shuhui Li, D.C. Wunsch, E.A. O'Hair and M.G. Giesselmann, "Using neural networks to estimate wind turbine power generation," *IEEE Trans. On Energy Conversion*, vol. 16, nº 3, Sept. 2001.

[9] R. Costello, D. McCoy, P. O'Donnell, A.G. Dutton and G.N. Kariniotakis, "Potential benefits of wind forecasting and the application of More-Care in Ireland," in *Proc. MED POWER 2002*. Athens, Greece, Nov. 2002.

[10] Decreto-Lei Nº 168/99, Ministério de Economia de Portugal. Lisbon, May 18, 1999.

[11] Decreto-Lei Nº 339-C/2001, Ministério da Economia e do Ordenamento do Território de Portugal. Lisbon, Dec. 29, 2001.

[12] A.G. Dutton, G. Kariniotakis, J.A. Halliday and E. Nogaret, "Load and wind power forecasting methods for the optimal management of isolated power systems with high wind penetration," *Wind Engineering*., vol. 23. nº 2, pp. 69-88

[13] European Union Directive 2001/77/EC, "On the promotion of electricity produced from renewable energy sources in the internal electricity market", *Official Journal of the European Communities L283*, Oct. 27, 2001.

[14] B.R. Szkuta, L.A. Sanabria and T.S. Dillon, "Electricity price short-term forecasting using artificial neural networks", *IEEE Trans. On Power Syst.*, vol. 14, pp.851-857, Aug. 1999.

[15] F.J. Nogales, J. Contreras, A.J. Conejo and R. Espínola, "Forecasting next-day electricity prices by time series models", *IEEE Trans. On Power Syst.,* vol. 17, nº 2, May 2002.

[16] E.D. Castronuovo, J.M. Campagnolo and R. Salgado, "New versions of nonlinear interior point methods applied to the optimal power flow," in *Proc. IEEE T&D 2002 Latin America*, São Paulo, Brazil, April 2002.

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